Study of the Permeability of Foam Conditioned Soils with Laboratory Tests

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Study of the Permeability of Foam Conditioned Soils with Laboratory Tests

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Abstract: Problem statement: EPB tunneling requires that the excavated soil has a plastic and pulpy behavior to be able to apply a stabilizing pressure to the face, but it should also be impervious to counteract filtration forces that could develop ahead of the face. The evaluation of this parameter in granular soil, before and after conditioning, is therefore of key importance for a correct conditioning agents choice. **Approach:** A new laboratory procedure for testing the permeability of conditioned soil with foam has been proposed. The tests have been carried out at different hydraulic loads, chosen to be 0.1 bars and 1 bar. **Results:** The proposed procedure has been applied to determine the behavior of differently conditioned granular soils: a fluvial sand and a pozzolanic soil and has shown that an increasing of the FIR induces a relative increase in the time required by water to pass through a standard sample, emphasizing, in this way, the effectiveness of the conditioning on impermeability of the soil. **Conclusion:** The tests have shown the laboratory procedure adequately captures the behavior of the conditioned soil. Further, the proposed test may also be used as an index for the preliminary definition of the quality of the soil conditioning and suitability for EPB tunneling.

Key words: Tunneling, Earth pressure balance shields, soil conditioning, laboratory tests, permeability test

INTRODUCTION

The application of EPB methodology for tunneling requires the excavated soil in the bulk chamber behind the cutter head should be characterized by a plastic and pulpy behavior to be able to apply the needed stabilizing pressure to the face (Merritt and Mair, 2006; Vinai *et al*., 2008; Peila *et al*., 2007; Cardu *et al*., 2009; Fuoco and Oreste, 2009). Besides other soil parameters, the permeability of the soil is very important since only a soil with low permeability is able to correctly apply the counter-pressure to the front when underground water is present in the soil to be excavated and can prevent the filtration from the front towards the bulk chamber (Quebaud *et al*., 1998; Peila *et al*., 2009). Filtration in these conditions induces destabilizing forces in the soil volume ahead of the tunnel face, requiring the theoretical application of higher stabilization forces for example when studied using the limit equilibrium method and the silo-theory (Anagnostou and Kovari, 1996). These authors indicate that a value of the permeability coefficient equal to 10^{-5} m*sec^{-1} is likely acceptable in order to prevent filtration flow and therefore eliminating the induced destabilizing force.

It is therefore of great importance in the planning and testing phase of a tunneling project to determine the optimal conditioning that may be achieved by the addition of foam and/or polymer conditioning agents to be able to quantify the level of impervious behavior of the conditioned soil.

In this context, it is fundamental to emphasize that the standard permeability test for a soil, as proposed from norms ASTM D2434 or CEN ISO/TS 17892-11, requires a water flow to be established in steady state regime through the test sample, this is not acceptable for conditioned soil, as it washes out the conditioning agents, such as the foam bubbles and therefore does not measure the true permeability of the conditioned soil (Borio *et al*., 2010). In order to solve this problem, studies and experiments have been carried out to develop a modified permeability test to appropriately measure the specific indicating parameters of the conditioned soil.

MATERIALS AND METHODS

The proposed test is developed using a sample of conditioned soil with the same volume and geometry of that contained in a standard permeameter (ASTM D2434) and applying to it a constant hydraulic pressure.

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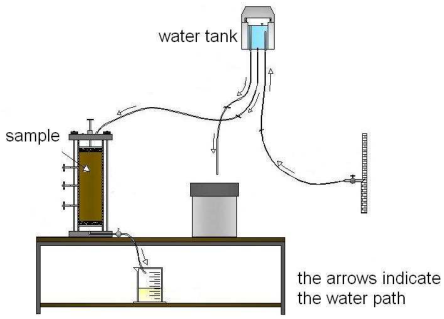


(a)

(b)

Fig. 1: Scheme (a) and photograph (b) of the used test equipment

In this way is possible to measure the time that is necessary to permit the passage of a standard amount of water through the sample (Fig. 1), that in this research was chosen to be two liters. This time therefore represents an index of impervious behavior achieved by conditioning the soil (I_i [s]) and quantifying the "difficulty" of the water to pass through the sample. In detail the test is executed following these steps: (Borio *et al*., 2010):

- Conditioning of the soil (Fig. 2): The foam is prepared using a foam generation unit (Peila *et al*., 2007) that permits to control the production parameters. Then the correct amount of the foam is then introduced in a standard concrete mixing bowl and is mixed with the soil till the foam has been completely absorbed by the soil
- Introduction of the soil in the cylinder and compaction by 8 hits of a Proctor hammer for every 10 cm thickness of placed soil
- Closing of the cylinder and application of water pressure

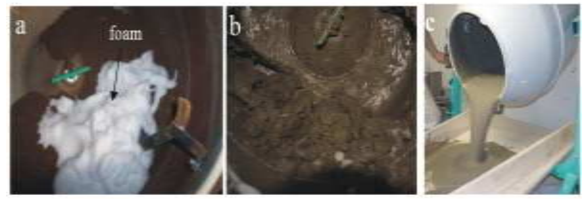


Fig. 2: Phase of soil mixing with the foam in the concrete bowl. (a) addition of the foam; (b) mixing phase; (c) pouring the conditioned soil after the mixing

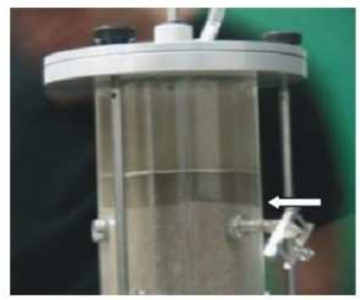


Fig. 3: Photograph of the permeameter during the test. The arrow indicates the position reached by the water inside the sample when the photograph was taken

- Measurement of the time that water takes to go through the sample (Fig. 3)

To verify the feasibility and the quality of results obtained using the proposed procedure, tests on two different types of conditioned granular soils were carried out.

RESULTS

The proposed modified permeability test to check the behavior of the conditioned soil has been applied on two different types of soil: a fluvial sand with a silt fraction equal to 5% and a pozzolanic soil with a silt fraction of 19% (Fig. 4); both conditioned with different amount of foam. The tests have been carried out at different hydraulic loads, chosen to be 0.1 bars and 1 bar in order to study the condition of urban tunneling with a low and a high water table load but that are to be considered as a standard test value. The foam that was used was obtained with a standard commercial foaming agent with a concentration in the generator fluid of 2% in volume and has a half time life of 200 sec when a FER of 12 is used and of 110 sec when a FER of 7.5 is used (Vinai *et al*., 2008).

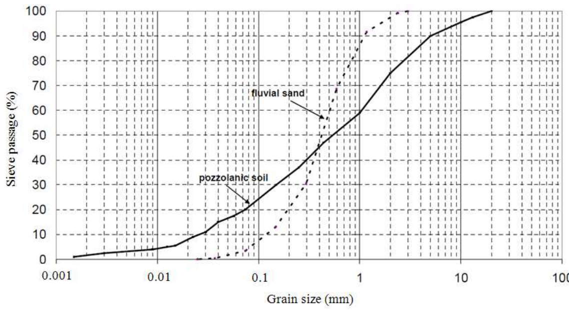
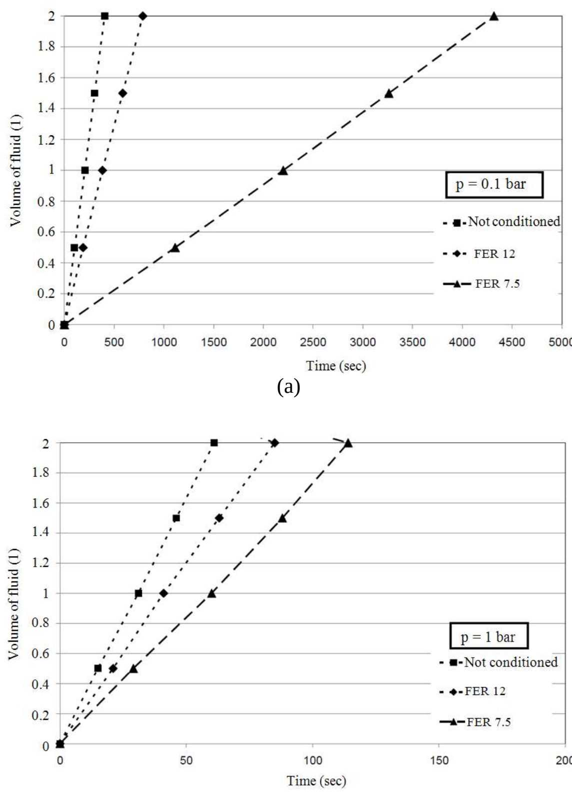


Fig. 4: Grain size distribution of tested soils



(a)

(b)

Fig. 5: Modified permeability test results on the tested fluvial sand with a conditioned obtained with a FIR = 40% at different FER values

Tests carried out on the fluvial sand: The result of the tests carried out on the sand show that the higher the foam content, the higher the time the water takes to go through the soil sample. Without conditioning, the sand index I_i when tested at the 0.1 bar pressure is equal to 403 sec, while a conditioned soil with FIR = 40% and a FER = 12 the I_i increases to 788 sec. It should be noted the sand contains a natural water content of 6%.

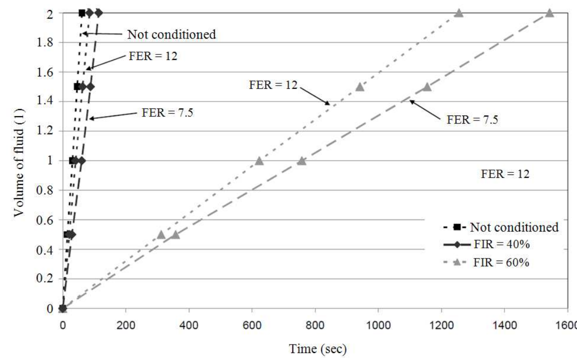


Fig. 6: Results of modified permeability tests at pressure p = 1 bar for different FIR values

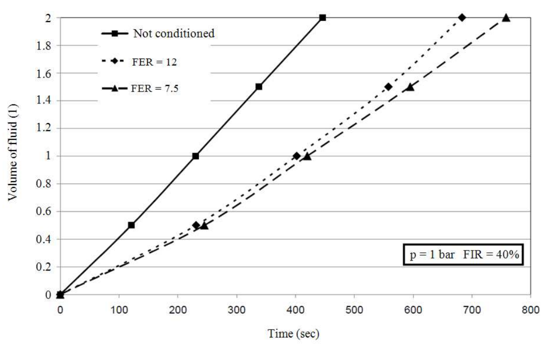
Furthermore, it was verified that reducing the FER and consequently using a “more wet” foam FER = 7.5 with FIR = 40% the conditioned sand becomes even more impermeable than in the previous case: at a pressure of 0.1 bars I_i increases to 4318 sec.

The previously described results change if the acting pressure on the sample is increased to 1 bar, as shown in Fig. 5 and 6. In this case, the speed of the water passing through the sample is higher but the influence of FIR is the same as that under 0.1 bar. As a conclusion, it can be said that at an applied pressure of 1 bar the foam produces a substantial increase in the soil impermeability, however it is not completely impermeable and water does continue to passes through the soil. For a FIR of 60% at 1 bar the difference in the behavior of the mix in comparison to a FIR of 40% is still more evident than those obtained with the tests at 0.1 bar: The index I_i for FIR = 60% and FER = 12 and for FIR = 60% and FER = 7.5 increases from 1250-1540 sec. This is considerably greater than the results obtained previously at 0.1 bar.

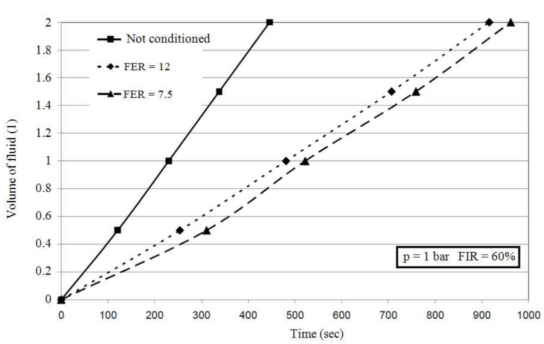
Test carried out on the pozzolanic soil: Pozzolanic soil, a fine sandy volcanic ash, is commonly encountered throughout several locations in Italy. The pozzolanic soil tested in these trials was sampled from the excavations of the Rome Metro and has a more heterogenous grain size distribution in comparison to the tested fluvial sand (Fig. 4). Initial tests of compacted and unconditioned pozzolanic soils were carried out at 0.1 bar pressure, however the samples were highly impermeable with I_i results higher than 4000s while for an applied pressure of 1bar a time of 446s was reached. The higher percentage of fines in the soil renders the natural compacted soil practically impermeable in relation to the adopted parameters of the modified permeability test. The addition of foam further increases the impermeability as well as improving the consistency and workability of the mix with reference to EPB excavation process as tested by Peila *et al*. (2007; 2009) and as shown in Fig. 7 where two slump test on these soil conditioned and unconditioned are compared. When the applied test pressure is increased to 1 bar, with FIR = 40% and FER = 12, a value of I_i equal to 670s is obtained and with FIR = 60% and FER = 12 an I_i value of 960s is obtained. The difference between the results obtained with FIR = 40% and FIR = 60% is in this case shows less of a difference (+43%) than the result obtained using the tested fluvial sand (+1300%) (Fig. 8 and 9).

(a) (b)

Fig. 7: Example of the behavior of the Rome Pozzolanic soil: Comparison of the slump tests of natural soil (a) and the conditioned one (b) with FER = 16, FIR = 25% and water content = 10%



(a)



(b)

Fig. 8: Results of modified permeability test on the Rome Pozzolanic soil

Comparison between the modified permeability test and the conventional permeability test: To form a relative basis from which the results from the modified test method with conditioned soils could be examined, ASTM D2434 was selected as the conventional permeability test method. This allows the proposed impermeability index, I_i, to be evaluated in common terms. This comparison has been executed on four different soils under a hydrostatic pressure of 1 bar: the two previously described (the fluvial sand and the pozzolanic soil), a silty sand and an artificial mix of sand and gravel (Fig. 10). The results obtained from these tests are presented in Table 1 and Fig. 11 and highlight the fact that an optimal correlation between the permeability (K) and the index of impermeability (I_i) can be easily set. For example, the value of K = 10-5, indicated as a good reference value for use in an EPB machine (Anagnostou and Kovari, 1996), corresponds to an index I_i of approximately 1800 sec when the test is executed to 1 bar. Thanks to this correlation it is possible to clearly estimate when a conditioned soil has reached a suitable permeability for use under EPB conditions.

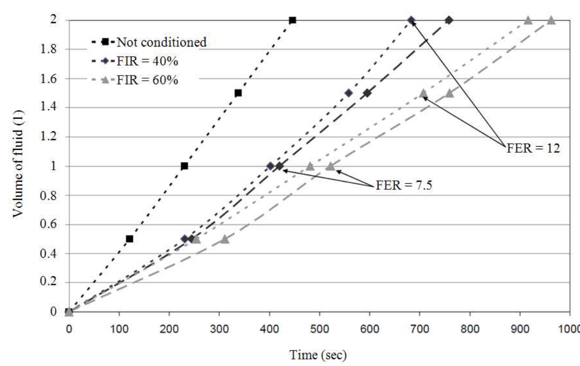


Fig. 9: Modified permeability test on the pozzolanic soil at a pressure of 1 bar

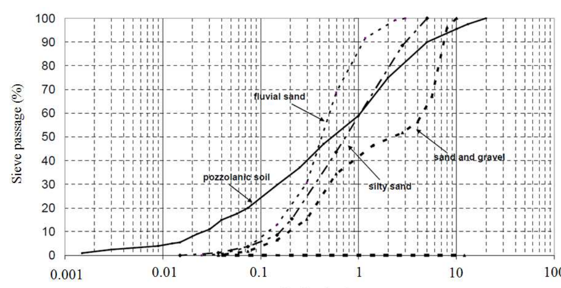


Fig. 10: Grain size curve distribution of the soils used for the comparison between the proposed index (I_i [s]) and the standard permeability coefficient (K [m sec^{-1}])

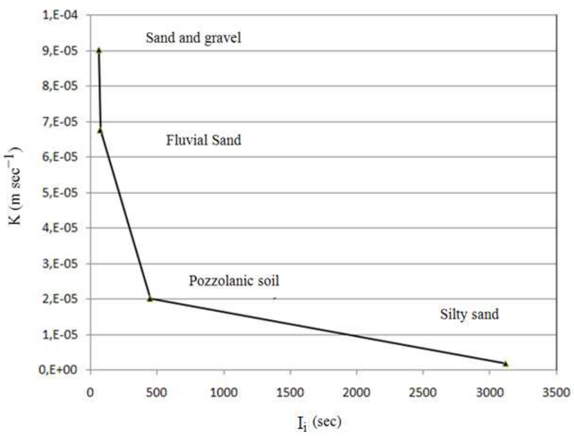


Fig. 11: Comparison between I_i (s) and K (m s^{-1}) for the tested natural cohesionless soils

Table 1: Comparison results between impermeability index as measured with the proposed procedure and the permeability measured as described in the ASTM D2434 standard on four different soil types at the pressure of 1 bar

Soil	K (m sec^{-1})	I_i (sec)
Silty sand	2.00E-6	3120
Pozzolanic soil	2.03E-5	446
Fluvial sand	6.77E-5	72
Sand and gravel	9.03E-5	63

DISCUSSION

Testing the impermeability of conditioned soils treated to permit EPB tunneling management is one of the key point for the laboratory choice of the optimal conditioning amount and foaming agents.

The standardized testing methodologies used to determine soil permeability have shown some limitations namely due to the flushing of the conditioning bubbles that are located in the inter-granular voids after the soil treatment. For this reason a simple, easy to use modified permeability test has been proposed and tested thus permitting the definition of an impermeability index (I_i) defined as the time it takes for the conventional volume of two liters of water to pass through a standard permeameter cylinder filled by conditioned soil, at a defined constant pressure, that can be used as a reference value. The application of the proposed test to two different soils, a fluvial sand and a pozzolanic soil, has shown that increasing of the FIR induces a relative increase in the time required, emphasizing the effectiveness of the conditioning on impermeability. Further, the proposed test may also be used as an index for the preliminary definition of the quality of the soil conditioning and suitability for EPB tunneling.

CONCLUSION

Conditioning by foaming agents and/or polymers plays a fundamental role in the execution of EPB tunneling. Modifying the properties and behavior of the soils to fulfill the specific needs of EPB conditions is essential. Besides other soil parameters such as plasticity, pulpy behavior and homogeneous low friction angle, the permeability of the soil is of great importance and it is therefore equally important to develop and perform tests of the true conditioned permeability, thereby guaranteeing proper control of the groundwater table during tunneling. The proposed testing procedure has shown to be a feasible tool for the assessment of the impermeability properties in granular soil thus helping the designers and job site managers in the preliminary choice of the best conditioning agent to be used for a specific tunnel.

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